Technical Report 169

EFFECT OF TEMPERATURE RISE ON COMPRESSIVE STRENGTH OF HARDENED CEMENT PASTE

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EFFECT OF TEMPERATURE RISE ON COMPRESSIVE STRENGTH OF HARDENED CEMENT PASTE

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Type C Final Report

by

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OBJECT OF TASK

To determine if the rate of heating cement paste of a concrete mix is a contributing factor to the explosive spalling that takes place when concrete pavement surfaces are subjected to thermal shock.

ABSTRACT

In connection with the effect of turbojet engine exhaust on concrete pavements, NCEL conducted two studies, one on the effect of temperature rise on cement paste, and one on the effect of thermal shock on concrete aggregates. The cement paste study is reported herein; a summary of the aggregate study is given in an appendix.

In this cement-paste study, 2-inch cubes made from three types of portland cement and two brands of calcium aluminate cement were cured, heated in a furnace from ambient to high temperatures (1000 to 1800 F) at different heating rates (8 to 14 F/sec), and tested in compression after cooling.

Heating decreased the compressive strength of cement-paste cubes. The higher heating rates produced no appreciable effect on the level of compressive strength or in the rate of decrease in strength with increase in maximum temperature. In general, the heated calcium aluminate cement cubes yielded a lower compressive strength than the heated portland cement cubes. An increase in curing and drying from 8 to 29 days produced no significant effect on the compressive strength of the heated cubes, but a

57-day curing and drying period resulted in a more stable compressive strength with respect to maximum temperature. All cubes cracked and some spalled when heated to the high temperatures. By statistical analysis, a straight line was found to represent adequately the relationship of compressive strength to maximum temperatures for each cement type, curing time and heating rate. The slope of the straight line was found to be significant for portland cements but not for the calcium aluminate cements.

On the basis of this study, it appears that rate of heating cement paste is not a contributing factor to spalling of concrete pavement surfaces subjected to thermal shock. On the basis of both the cement-paste and aggregate studies, it appears preferable to have the cement paste and aggregates as dry as possible before the concrete is subjected to high thermal-shock conditions.

A recommendation is given to conduct an investigation to determine the refractoriness of concrete slabs under field conditions.

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INTRODUCTION

The operation of modern Navy turbojet aircraft subjects airfield pavements to some severe conditions. To accommodate these aircraft safely and efficiently, airfield pavements must be able to carry heavy wheel loads with high tire pressures, possess good skid resistance, and have enough refractory qualities to resist the high-temperature and high-velocity exhaust gases of jet engines. The pavements must also resist the effects of jet fuel spillage and be free from loose fragments of aggregate or other materials that might be drawn into the jet intake and cause serious damage to the engine.

These requirements have necessitated continued research to find improved pavement materials. In studies of the effect of jet engine exhaust on pavement, NCEL evaluated a number of portland cement concrete pavements. Damage in the form of spalling of some concrete pavement surfaces was observed during exposure to afterburner power. In an effort to determine the cause or causes of the damage, two separate investigations were conducted, one on cement paste and one on concrete aggregates. The cement paste investigation is reported herein; a summary of the concrete aggregate study is given in Appendix A.

In the cement-paste investigation, the plan was to determine the compressive strength of 2-inch cement-paste cubes after heating in a furnace to high temperatures at various heating rates. A correlation was anticipated between the level of compressive strength and the heating rate.

TEST EQUIPMENT

A gas-fired brick furnace with an opening on top, shown in Figure 1, was used to heat the cement-paste cubes to high temperatures. The size of the furnace chamber was 10 inches by 18-1/2 inches by 11 inches deep.

A blower with an output of 150 cfm supplied air through a diaphragm valve to two adjustable proportional air-gas mixers. The mixture was in turn conveyed to two burner nozzles located near diagonally opposite corners of the furnace chamber. The exhaust gas was expelled through a smokestack connected to a port located in the base of the furnace chamber.

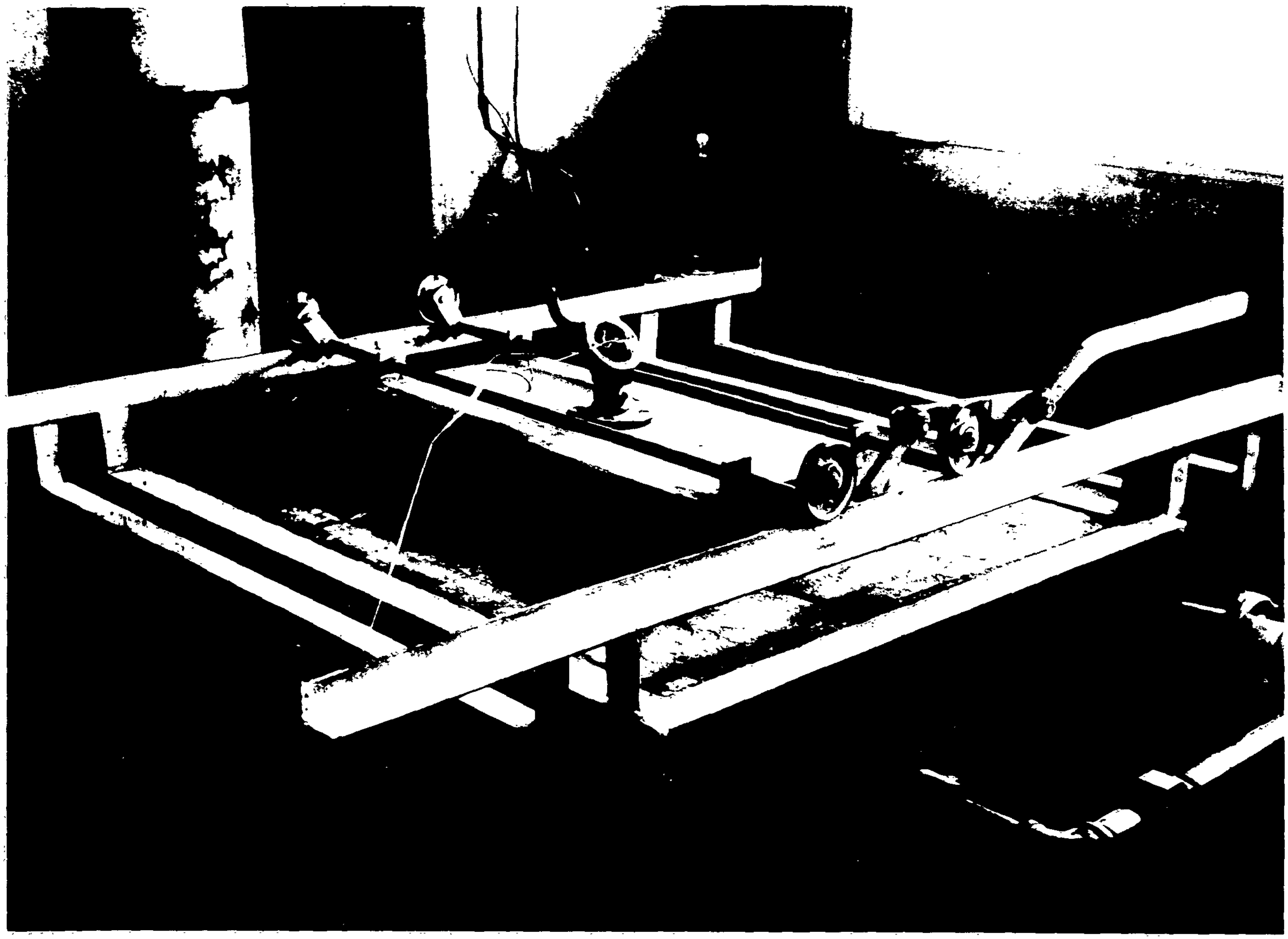

Figure 1. Gas-fired furnace.

A circular-chart pneumatic program controller with a chromel-alumel thermocouple protruding approximately 1/2 inch below the furnace lid was used to control the furnace temperature. This instrument, shown in Figure 2, consisted of motor-driven cams cut to various time-temperature profiles, a cam follower connected by a cable to a set-point indicator, a pneumatic control unit and a primary element. As the cam rotated, the cam follower moved the set-point indicator. The indicator in turn changed the controlled pressure of the pneumatic control unit connected to the diaphragm valve. Thus the volume of air-gas mixture was regulated to obtain the furnace temperature indicated on the cam at any time. Likewise, when the cam was stopped at a certain index, the temperature was maintained at the indicated level.

With the pneumatic program controller, it was possible to raise the furnace temperature from about 200 to 2000 F at constant rates of approximately 8 to 14 degrees per second. It was also possible to maintain any temperature between approximately 1000 to 2000 Fahrenheit. It appeared that the furnace with the controller was capable of producing temperatures equivalent to those on pavement surfaces being subjected to turbojet engine exhausts. However, there were no impinging gas velocities approaching those of jet engine exhausts.

CEMENT FOR TEST

Types I, II and III portland cement and two calcium aluminate cements were obtained for this investigation and stored in sealed metal drums. One calcium aluminate cement was manufactured in England and the other in the United States; for the purpose of this report these cements were designated as Cement A and Cement B, respectively.

The predominant compound in calcium aluminate cement is calcium aluminate while that of portland cement is a combination of calcium silicates. Under the influence of high temperatures, calcium aluminate has much greater resistance to destruction than calcium silicates.* Thus calcium aluminate cements are used in refractory concrete for furnaces, ovens, kilns and other heating units.

* R. A. Heindl and Z. A. Post. "Refractory Castables: Preparation and Some Properties." Journal of the American Ceramic Society, Vol. 33, No. 7 (July 1950), p. 230.

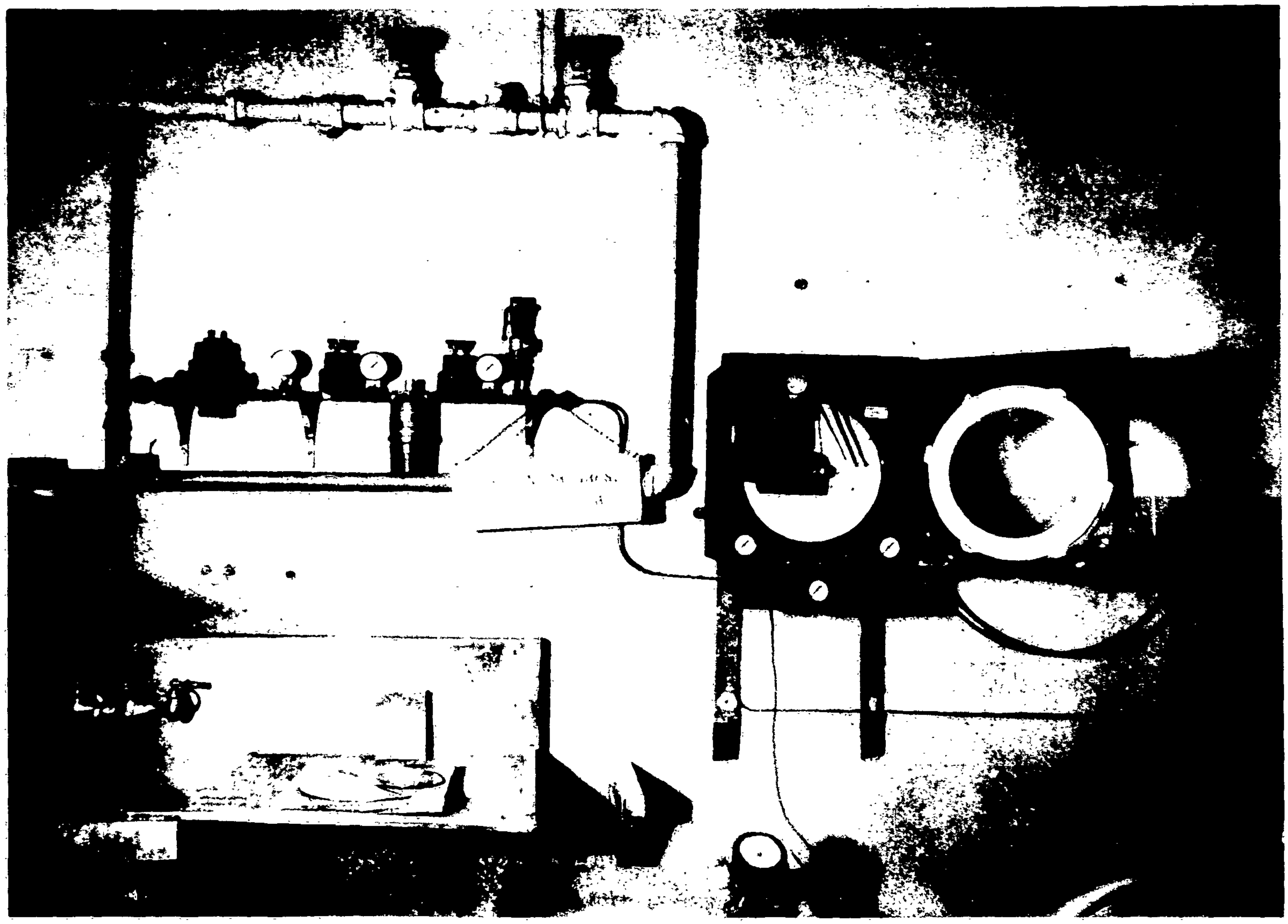

Figure 2. Circular-chart pneumatic program controller.

METHOD OF TEST

Specimens, Molds, and Proportioning

The specimens used for compressive-strength determinations were 2-inch cubes. Steel molds containing 12 compartments were used for the cubes, and each batch was mixed for 12 cubes. The ratio of portland cement to water was 3000 grams to 1050 milliliters. This ratio for calcium aluminate cement yielded a paste with excessive flow, and, after a number of trial batches, a cement-water ratio of 3000 grams to 825 milliliters was adopted.

Mixing

The following method of mixing, specified by ASTM Designation C243-58T, was adopted, using a mechanical mixer which was in accordance with ASTM Designation C305-58T. The inner side of the bowl was wiped clean with a damp cloth and the mixing water was placed in the bowl. The cement was added and mixed for three minutes at the low speed. The mixing was then stopped for three minutes. During this standing period any paste collected on the side was scraped down into the batch, and the bowl was covered with a damp cloth. Then the paste was mixed for an additional three minutes at the low speed.

Molding

As soon as the mixing was completed, the cement paste was molded. The 12 compartments of the mold were filled in three layers. Each layer of cement paste in each compartment was tamped 20 times with a tamper 1/2 inch by 1 inch by 6 inches long, made of nonabsorbtive material. The top of the specimens was smoothed with a trowel, and the excessive cement paste was trimmed flush with the top of the mold with a sawing motion of a straightedge.

Curing

Immediately upon completion of molding, the mold with the specimens was stored in a moist cabinet at 73.4 ± 2 F and 95 to 100 percent relative humidity. At the end of 24 hours the specimens were removed from the mold and given additional curing and drying. This included storage in the moist cabinet and, in some cases, drying in a 73.4 ± 2 F and 50 ± 2 percent relative humidity room. Finally, all specimens were dried in an oven at 100 ± 2 F for 24 hours before heating. Table I shows the curing and drying schedules used for each type of cement. No 28-day curing in the moist cabinet was used for the high early-strength cements (Type III and Cements A and B), because these cements were expected to attain most of their full strength in 7 days.

Table I. Curing and Drying Schedule for Cement-Paste Cubes

Cement Type	Curing and Drying (days)			
	73.4 ± 2 F and 95-100% RH	73.4 ± 2 F and 50 ± 2% RH	100 F	Total
I and II	7	-	1	8
	28	-	1	29
	7	49	1	57
III, A and B	7	-	1	8
	7	21	1	29
	7	49	1	57

Heating

After drying, 24 cubes from two molds were weighed and their weights recorded. The 24 cubes were made from the same type of cement and cured and dried in the same manner. Six cubes, three per mold, were set aside for unheated compressive-strength determinations. Three cubes from one mold were put in a furnace pan made of heat-resistant metal and placed in the gas-fired furnace. The controller was set to a rate of temperature rise, the furnace was lighted, the furnace chamber was immediately covered, and the cam drive switch on the temperature controller was turned on. When the furnace temperature reached the first maximum temperature (1000 F), the furnace was turned off, immediately uncovered, and the pan with the cubes was removed. The cubes were then taken from the pan and cooled in a ventilated cabinet. Subsequent heatings of the remaining cubes were made at the same heating rate, with 1200, 1400, 1500, 1600 and 1800 F as maximum temperatures. Before each heating, the furnace was cooled to 200 F or below.

The selection of 1500 F was based on BuAer and BuDocks design requirements. Enclosure (1) of BuAer Notice 11012 of September 1957 stated that blast-resistant pavements shall be designed to withstand a temperature of 1500 F, and NavDocks Specification S-P16 (drawing No. 900464) of April 1960 stated that blast deflectors were designed for a maximum temperature of 1500 Fahrenheit. However, changes in jet aircraft design and operation in the future may require pavements and blast deflectors to withstand a higher maximum temperature. Therefore, 1600 and 1800 F were included in the investigation. The maximum temperatures below 1500 F were arbitrarily selected.

For each type of cement and each curing and drying time, four rates of temperature rise were used. These were 8, 10, 12 and 14 degrees per second. The selection of these rates of heating was based on some unpublished time-temperature profiles obtained from thermocouples on surfaces of concrete pavements evaluated under a jet engine at NCEL. These profiles indicated that pavement surfaces were subjected to rates of heating from approximately 7 to 16 F per second during exposure to afterburner power.

Testing in Compression

Upon cooling, approximately 1-1/2 hours after heating, the cubes were reweighed to determine changes in weight. Compressive strengths of the heated and unheated cubes were then determined. The procedure for testing 2-inch cubes in ASTM method C109-58 was followed in general. No initial loading was applied, and a rate of loading of 40,000 pounds per minute was used in compressing each cube.

TEST RESULTS

Tables II through XVI in Appendix B show the compressive strengths of the heated and unheated cement-paste cubes made from the five different types of cement cured and dried as shown on Table I. An analysis of the test results was conducted by the Corporation of Economics, Industry and Research, a firm under contract to NCEL for statistical studies and data analyses. The details of the analysis and results based on the analysis are given in the CEIR report which is in Appendix C. A summary of the findings of that study is given below.

For each cement type, curing schedule and heating rate, it was proposed that a straight line adequately represented the relationship of compressive strength to maximum temperature. The parameters of the straight-line equation were estimated from the average observed compressive strengths by the method of least squares.

By quantitative analysis, it was found that the computed values were in good agreement with the observed compressive strengths. Therefore, the parameters of the proposed model were considered meaningful and were analyzed for the effect of heating rate, curing and drying time, and cement type.

The average β, or the average measure of the rate of decrease of compressive strength, was -20.8 for the low heating rates (8 and 10 per second), and -25.9 for the high rates (12 and 14 F per second).

There was no appreciable difference between the average β for the cubes cured and dried for 8 days and those cured and dried for 29 days. However, the average β was -27.7 for the 8-day and 29-day cubes, while it was only -14.7 for the 57-day cubes.

The average β was -39.0 for the three portland cements, and zero for the two calcium aluminate cements. The average compressive strength (μ) per heating rate was 1485 psi for all heated portland cement-paste cubes, and 1125 psi for all heated calcium aluminate cement-paste cubes.

DISCUSSION OF TEST RESULTS

Popping of the cubes was sometimes heard during heating. This generally occurred at the higher temperatures. Observations after heating showed that all cubes were cracked and appeared to be dry. Figure 3 shows two cubes before heating and two after heating. Some were damaged in the form of spalling. Compression tests were not made on the cubes which were damaged extensively, and the test results for these cubes are not reported.

From the determinations of weights before and after heating, it appeared that the cubes lost some weight. The weights determined after heating were not accurate since the dislodged fragments were usually lost in the furnace. Therefore, the weight decrements are not reported.

Caution was exercised in selecting the two best opposite faces to contact the upper and lower bearing blocks of the testing machine. No appreciable curvatures or irregularities were found on the contact faces of the unheated cubes. Curvatures were found on some of the contact faces of heated cubes, but grinding of these faces as specified in ASTM Method C109-58 was omitted to avoid further damage of the already cracked cubes.

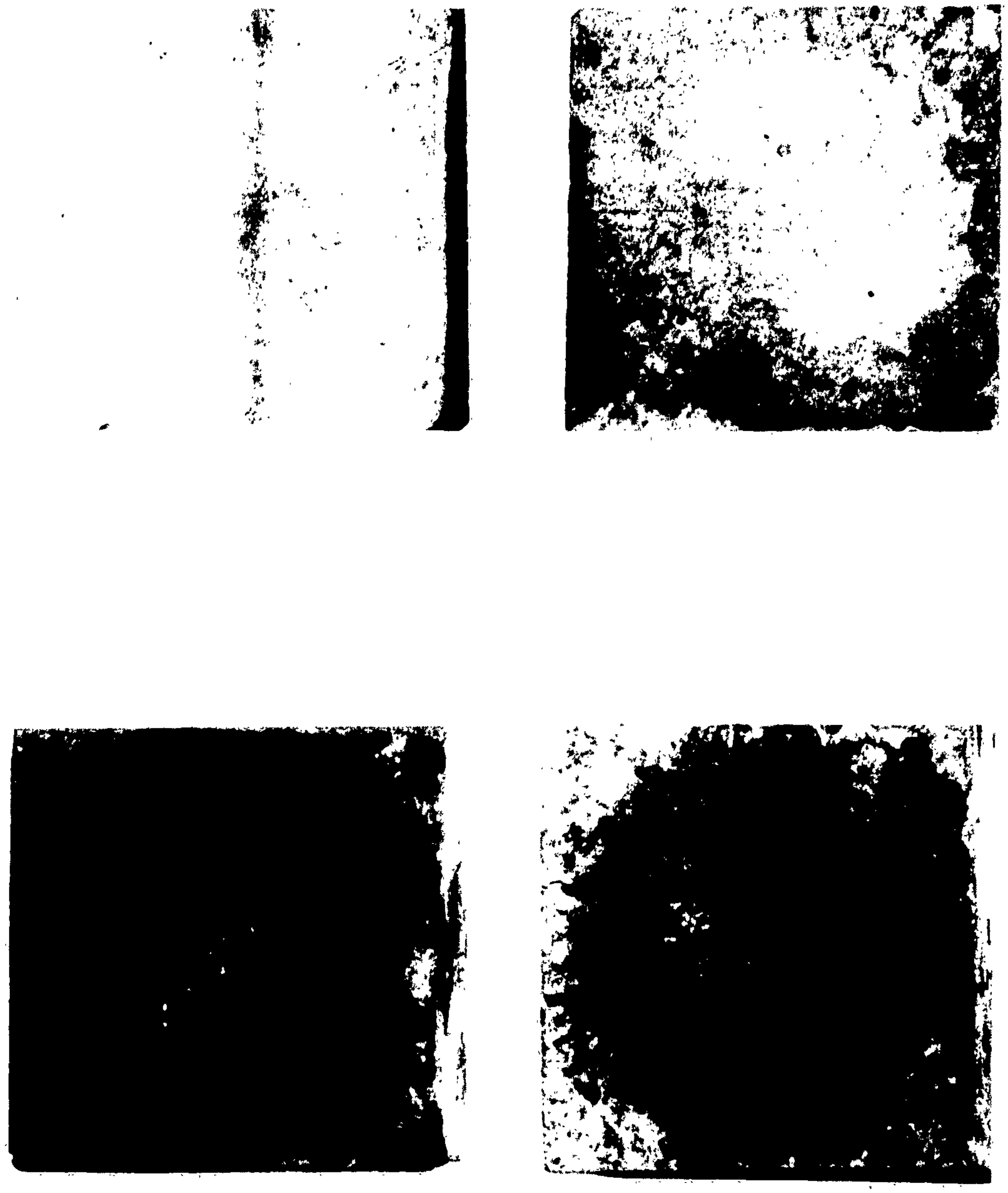

Figure 3. Cement-paste cubes before and after heating.

SIGNIFICANT FINDINGS

1. Heating of 2-inch hardened cement-paste cubes from ambient to a maximum temperature range of 1000 to 1800 F at heating rates of 8 to 14 F per second caused a decrease in compressive strength.

2. Based on a 95-percent confidence level, the higher heating rates produced no appreciable effect on the level of compressive strength or in the rate of decrease in strength with increased maximum temperature.

3. In general, the heated calcium aluminate cement cubes yielded a lower average compressive strength than did the heated portland cement cubes. The rate of decrease in compressive strength with increase in maximum temperature was lower for the calcium aluminate cement cubes than for the portland cement cubes.

4. The increase in curing and drying from 8 to 29 days produced no significant effect on the compressive strengths, but the 57-day curing and drying resulted in a lower rate of decrease in compressive strength with increase in maximum temperature.

5. All heated cubes cracked and some experienced damage in the form of spalling.

6. It was found that a straight-line equation adequately represents the relationship of compressive strength to maximum temperature for each cement type, curing condition and heating rate. The slope of the straight line was found to be significant for the portland cements but not for the calcium aluminate cements.

CONCLUSIONS

1. Since higher heating rates produced no significant effect on the level or rate of decrease in compressive strength with increased maximum temperature, it appears that rate of heating cement paste is not a contributing factor to spalling of concrete pavement surfaces subjected to thermal shock.

2. On the basis of the effect of curing time on the compressive strength of hardened cement-paste cubes in this study, and on the basis of the breakdown of the oven-dried and saturated-surface-dried aggregates under thermal shock in the concrete aggregate study (see Appendix A), it appears preferable to have the cement paste and aggregate as dry as possible before the concrete is subjected to high thermal-shock conditions.

RECOMMENDATION

Since separate studies, one on cement pastes and one on concrete aggregates, were conducted, it is recommended that an investigation based on the two studies be made to determine what combination of the factors would form a suitable jet-blast-resistant concrete.

Appendix A

SUMMARY OF TR-170, "EFFECT OF AGGREGATE SIZE ON THERMAL SHOCK RESISTANCE"

The objective of this task is to determine if the size of the aggregate used in a concrete mix is a contributing factor to the explosive spalling that takes place when concrete pavement surfaces are subjected to thermal shock.

In this study, two river gravels, one diabase, one blast-furnace slag, and one expanded shale aggregate were segregated into five sizes (1-inch, 3/4-inch, 1/2-inch, 3/8-inch, and No. 4). Each size of aggregate in the oven-dried and saturated-surface-dried conditions was subjected to thermal shock in a gas-fired furnace at temperatures ranging from 1000 to 2000 Fahrenheit. Breakdown of the various sizes was established by comparing the before-heating and after-heating sieve analyses.

It was found that heating caused breakdown of the aggregates. By statistical analysis, it was determined that the larger sizes of aggregate had more breakdown than the smaller ones, and that the higher temperatures caused more breakdown than the lower temperatures. It was also determined that the saturated-surface-dried aggregates had higher breakdown than the oven-dried aggregates.

It appears from this investigation that smaller aggregates are preferable to larger aggregates for heat-resistant concrete.

Appendix B

COMPRESSIVE STRENGTH DATA
(Tables II – XVI)

Table II. Compressive Strength of Type I Portland Cement-Paste Cubes Cured and Dried for 8 Days

Cube No.	Maximum Temperature (F)	Rate of Temperature Rise							
		8 F/sec		10 F/sec		12 F/sec		14 F/sec	
		1	2	1	2	1	2	1	2
1	Not Heated	5,553		8,955		6,181		5,519	
2		9,558	7,186	6,968	7,304	5,702	5,926	5,808	5,568
3		6,448		5,988		5,896		5,378	
4	1000	5,075		5,392		5,576		4,797	
5		6,206	5,819	5,560	5,380	5,837	5,504	5,050	4,957
6		6,175		5,188		5,098		5,025	
7	1200	6,228		5,090		4,963		4,775	
8		6,733	6,461	5,224	5,180	5,167	5,093	4,747	4,743
9		6,421		5,226		5,149		4,708	
10	1400	4,937		-		4,730		4,227	
11		5,000	4,987	5,089	3,817	5,000	4,651	4,291	4,339
12		5,025		2,545		4,223		4,500	
1	Not Heated	5,808		7,299		6,684		6,939	
2		5,418	6,590	5,988	6,682	6,452	6,436	6,849	7,134
3		8,544		6,759		6,173		7,614	
4	1500	5,431		4,384		4,295		4,218	
5		4,881	5,351	5,150	4,668	4,684	4,330	4,300	4,205
6		5,740		4,471		4,010		4,098	
7	1600	4,340		4,301		4,422		3,659	
8		5,228	4,245	5,000	4,744	4,213	4,213	4,279	4,042
9		3,168		4,924		4,003		4,188	
10	1800	4,672		4,178		4,219		4,179	
11		4,329	3,800	-	3,840	3,375	3,679	3,925	4,089
12		2,399		3,508		3,444		4,163	

1. Compressive strength (psi)
2. Average compressive strength (psi)

Table III. Compressive Strength of Type I Portland Cement-Paste Cubes Cured and Dried for 29 Days

Cube No.	Maximum Temperature (F)	Rate of Temperature Rise							
		8 F/sec		10 F/sec		12 F/sec		14 F/sec	
		1	2	1	2	1	2	1	2
1		9,284		9,279		9,204		8,025	
2	Not Heated	9,574	9,390	9,950	9,852	8,433	9,079	7,218	7,621
3		9,311		10,326		9,601		7,619	
4		6,583		7,928		7,275		6,863	
5	1000	7,250	6,888	8,159	7,959	8,060	7,630	7,043	6,807
6		6,831		7,789		7,556		6,516	
7		6,742		6,526		7,707		5,845	
8	1200	6,688	6,882	6,853	6,704	8,259	7,535	5,840	6,108
9		7,217		6,733		6,638		6,638	
10		6,053		7,075		6,917		5,909	
11	1400	5,529	6,108	7,388	6,884	7,188	6,969	6,023	6,211
12		6,742		6,190		6,803		6,700	
1		9,474		9,714		9,465		9,545	
2	Not Heated	8,638	9,195	9,639	9,814	8,993	9,262	7,519	8,491
3		9,474		10,088		9,328		8,410	
4		6,182		6,452		5,970		5,587	
5	1500	6,091	6,083	6,880	6,136	6,501	5,635	6,688	5,937
6		5,975		5,075		4,433		5,535	
7		6,688		5,545		4,490		6,206	
8	1600	5,614	5,926	5,568	5,619	5,727	4,643	6,266	6,218
9		5,476		5,743		3,712		6,181	
10		5,302		4,738		5,139		5,565	
11	1800	5,025	5,160	5,200	4,887	6,025	5,632	5,702	5,621
12		5,153		4,724		5,732		5,595	

1. Compressive strength (psi)
2. Average compressive strength (psi)

Table IV. Compressive Strength of Type I Portland Cement-Paste Cubes Cured and Dried for 57 Days

Cube No.	Maximum Temperature (F)	Rate of Temperature Rise							
		8 F/sec		10 F/sec		12 F/sec		14 F/sec	
		1	2	1	2	1	2	1	2
1	Not Heated	4,950		7,676		8,564		8,191	
2		5,678	5,706	7,266	7,625	7,708	8,299	7,763	8,103
3		6,490		7,934		8,624		8,354	
4	1000	4,280		5,222		6,294		7,217	
5		4,848	4,552	5,831	5,736	5,672	5,831	6,450	6,932
6		4,527		6,156		5,528		7,128	
7	1200	4,229		5,270		5,772		5,563	
8		4,530	4,390	6,005	5,670	5,560	5,546	6,935	6,422
9		4,411		5,736		5,305		6,768	
10	1400	5,322		4,527		4,517		5,600	
11		5,433	4,882	5,179	4,781	4,699	4,653	5,515	5,820
12		3,892		4,637		4,744		6,344	
1	Not Heated	5,736		6,179		6,958		8,766	
2		6,859	6,636	6,998	6,670	7,337	7,638	8,000	8,395
3		7,312		6,832		8,619		8,418	
4	1500	4,987		5,136		5,050		5,263	
5		4,988	4,784	4,815	4,984	4,772	4,953	6,328	5,602
6		4,378		5,000		5,038		5,215	
7	1600	4,798		4,565		6,000		5,063	
8		5,500	5,166	4,433	4,376	4,713	5,084	5,525	5,319
9		5,199		4,129		4,539		5,369	
10	1800	4,570		4,279		5,354		5,557	
11		3,234	4,092	5,313	4,743	4,774	4,790	5,332	5,334
12		4,472		4,637		4,241		5,112	

1. Compressive strength (psi)
2. Average compressive strength (psi)

Table V. Compressive Strength of Type II Portland Cement-Paste Cubes Cured and Dried for 8 Days

Cube No.	Maximum Temperature (F)	Rate of Temperature Rise							
		8 F/sec		10 F/sec		12 F/sec		14 F/sec	
		1	2	1	2	1	2	1	2
1	Not Heated	3,329		6,725		7,545		9,560	
2		8,664	6,943	7,788	7,067	7,168	7,986	9,369	9,608
3		8,836		6,688		9,246		9,896	
4	1000	6,492		6,163		7,494		8,553	
5		6,541	6,891	6,744	6,314	6,667	7,069	8,203	7,924
6		7,641		6,034		7,046		7,015	
7	1200	6,234		6,650		5,960		8,538	
8		6,964	6,209	6,836	6,416	6,743	6,352	8,954	8,746
9		5,430		5,762		-		-	
10	1400	6,573		5,267		2,826		6,801	
11		6,808	6,261	5,113	5,384	4,793	4,613	8,072	7,352
12		5,402		5,772		6,221		7,183	
1	Not Heated	8,211		7,416		7,824		9,768	
2		8,562	8,148	7,995	7,544	8,593	8,153	10,443	9,821
3		7,671		7,221		8,041		9,251	
4	1500	5,720		5,503		5,759		6,193	
5		5,674	5,417	5,802	5,652	5,313	5,446	8,321	7,257
6		4,856		-		5,266		-	
7	1600	5,495		4,664		-		-	
8		6,421	5,851	5,040	4,495	5,000	5,323	8,159	8,159
9		5,636		3,781		5,646		-	
10	1800	5,051		4,590		5,388		-	
11		4,848	4,011	5,402	5,245	4,439	4,914	6,134	6,134
12		2,133		5,744		-		-	

1. Compressive strength (psi)
2. Average compressive strength (psi)

Table VI. Compressive Strength of Type II Portland Cement-Paste Cubes Cured and Dried for 29 Days

Cube No.	Maximum Temperature (F)	Rate of Temperature Rise							
		8 F/sec		10 F/sec		12 F/sec		14 F/sec	
		1	2	1	2	1	2	1	2
1	Not Heated	8,577		11,716		13,173		12,143	
2		9,470	9,041	11,576	11,010	11,372	12,241	10,860	11,241
3		9,076		9,739		12,179		10,721	
4	1000	9,603		10,636		10,332		6,738	
5		7,113	8,126	8,864	9,610	11,048	10,783	10,686	8,633
6		7,663		9,330		10,969		8,475	
7	1200	6,675		7,748		9,949		9,167	
8		7,895	7,220	9,039	7,854	10,846	10,189	8,596	7,684
9		7,089		6,774		9,772		5,290	
10	1400	6,015		7,586		9,232		6,783	
11		5,990	5,819	9,074	8,210	9,122	9,376	8,333	7,915
12		5,453		7,970		9,773		8,629	
1	Not Heated	8,890		12,698		13,392		12,030	
2		9,152	9,092	11,034	12,010	11,960	12,682	11,470	11,857
3		9,235		12,297		12,695		12,071	
4	1500	6,141		5,650		9,460		8,010	
5		7,577	6,531	8,718	6,732	9,429	9,200	8,112	8,301
6		5,876		5,829		8,711		8,781	
7	1600	7,475		8,552		9,266		3,728	
8		6,106	6,290	8,686	7,408	8,509	8,759	7,854	6,352
9		5,288		4,986		8,503		7,475	
10	1800	5,476		8,905		6,875		3,470	
11		5,995	5,780	3,673	5,655	8,423	7,486	6,870	5,738
12		5,870		4,387		7,161		6,873	

1. Compressive strength (psi)
2. Average compressive strength (psi)

Table VII. Compressive Strength of Type II Portland Cement-Paste Cubes Cured and Dried for 57 Days

Cube No.	Maximum Temperature (F)	Rate of Temperature Rise							
		8 F/sec		10 F/sec		12 F/sec		14 F/sec	
		1	2	1	2	1	2	1	2
1	Not Heated	8,015		8,325		8,643		7,844	
2		7,730	7,429	7,675	8,132	8,450	8,693	8,106	7,941
3		6,541		8,396		8,987		7,872	
4	1000	6,486		4,520		6,889		6,899	
5		5,936	6,156	5,220	5,222	7,411	6,924	5,838	6,797
6		6,046		5,950		6,472		7,655	
7	1200	6,250		5,596		6,100		7,719	
8		5,886	6,227	5,361	5,664	4,937	5,393	6,540	7,300
9		6,546		6,036		5,141		7,640	
10	1400	5,771		4,668		7,430		5,736	
11		6,253	6,204	-	5,054	5,419	6,711	6,612	6,044
12		6,589		5,440		7,284		5,784	
1	Not Heated	7,318		8,005		9,253		7,170	
2		7,854	7,728	8,929	8,995	9,810	9,355	8,160	8,227
3		8,013		10,052		9,003		9,352	
4	1500	6,308		7,436		6,279		6,097	
5		5,814	5,884	6,514	6,902	6,456	5,945	6,604	6,715
6		5,529		6,756		5,101		7,444	
7	1600	5,812		6,330		6,613		6,637	
8		5,215	5,495	6,793	6,535	6,318	6,119	5,236	5,637
9		5,457		6,481		5,425		5,038	
10	1800	5,076		5,878		-		5,934	
11		5,321	5,226	6,802	6,363	4,518	5,085	5,776	5,726
12		5,282		6,408		5,651		5,468	

1. Compressive strength (psi)
2. Average compressive strength (psi)

Table VIII. Compressive Strength of Type III Portland Cement-Paste Cubes Cured and Dried for 8 Days

Cube No.	Maximum Temperature (F)	Rate of Temperature Rise							
		8 F/sec		10 F/sec		12 F/sec		14 F/sec	
		1	2	1	2	1	2	1	2
1	Not Heated	9,111		9,900		9,810		9,948	
2		9,812	9,201	10,248	10,083	10,889	10,174	9,945	10,054
3		8,681		10,100		9,823		10,269	
4	1000	6,892		7,750		8,379		8,658	
5		5,822	6,707	7,980	7,645	8,531	8,168	8,961	8,487
6		7,406		7,204		7,593		7,842	
7	1200	6,265		7,220		7,738		6,603	
8		6,995	6,467	7,728	7,030	7,786	7,507	6,231	6,151
9		6,140		6,143		6,997		5,619	
10	1400	5,150		6,385		7,411		6,061	
11		5,476	5,396	7,437	6,988	7,866	7,480	6,158	5,308
12		5,563		7,143		7,162		3,704	
1	Not Heated	7,518		10,463		10,770		9,723	
2		8,419	8,526	10,425	10,262	10,856	10,533	11,315	10,338
3		9,641		9,899		9,974		9,975	
4	1500	4,230		6,789		6,357		5,805	
5		4,465	4,439	6,926	6,497	5,888	5,986	6,481	6,098
6		4,623		5,776		5,714		6,009	
7	1600	5,099		5,244		7,055		5,336	
8		5,272	4,961	6,319	5,627	6,379	6,578	5,669	5,713
9		4,512		5,318		6,301		6,135	
10	1800	4,490		5,535		5,776		4,218	
11		4,713	4,688	5,050	5,534	5,481	5,757	2,635	4,475
12		4,862		6,018		6,015		6,573	

1. Compressive strength (psi)
2. Average compressive strength (psi)

Table IX. Compressive Strength of Type III Portland Cement-Paste Cubes Cured and Dried for 29 Days

Cube No.	Maximum Temperature (F)	Rate of Temperature Rise							
		8 F/sec		10 F/sec		12 F/sec		14 F/sec	
		1	2	1	2	1	2	1	2
1	Not Heated	8,939		8,879		7,000		7,066	
2		8,602	8,609	8,838	9,247	8,753	8,514	9,085	8,692
3		8,287		10,025		9,788		9,924	
4	1000	6,548		6,378		7,550		7,977	
5		7,374	6,868	7,657	6,959	6,505	6,688	7,406	7,519
6		6,684		6,842		6,010		7,173	
7	1200	7,292		5,884		6,038		6,382	
8		5,751	6,423	5,963	6,453	6,463	6,139	6,658	6,759
9		6,225		7,513		5,917		7,236	
10	1400	6,396		6,041		6,303		6,332	
11		5,876	5,939	5,088	5,591	6,050	5,897	5,965	6,396
12		5,546		5,646		5,339		6,892	
1	Not Heated	8,929		10,203		9,499		10,138	
2		8,932	8,630	9,722	9,911	9,975	9,921	8,120	9,236
3		8,030		9,808		10,288		9,449	
4	1500	5,362		4,809		5,763		6,272	
5		5,951	5,607	6,582	5,766	6,025	5,793	6,521	6,090
6		5,507		5,908		5,590		5,477	
7	1600	4,148		5,749		6,754		5,050	
8		4,597	4,649	6,285	5,877	5,375	6,030	5,226	5,400
9		5,201		5,596		5,963		5,925	
10	1800	5,000		4,564		6,310		5,678	
11		4,560	4,832	4,271	4,749	4,673	5,272	5,779	5,467
12		4,937		5,413		4,834		4,949	

1. Compressive strength (psi)
2. Average compressive strength (psi)

Table X. Compressive Strength of Type III Portland Cement-Paste Cubes Cured and Dried for 57 Days

Cube No.	Maximum Temperature (F)	Rate of Temperature Rise							
		8 F/sec		10 F/sec		12 F/sec		14 F/sec	
		1	2	1	2	1	2	1	2
1	Not Heated	8,929		8,388		7,075		7,426	
2		10,940	9,310	7,870	8,455	7,256	7,587	8,486	8,284
3		8,060		9,108		8,429		8,940	
4	1000	6,319		4,988		5,353		6,420	
5		5,213	5,657	5,323	5,518	6,030	5,855	7,106	6,495
6		5,438		6,244		6,181		5,958	
7	1200	6,010		6,439		5,238		6,025	
8		5,480	5,530	4,638	5,991	5,174	5,250	5,285	5,544
9		5,100		6,897		5,338		5,323	
10	1400	3,634		4,912		4,762		4,356	
11		-	4,790	4,925	5,394	6,003	5,499	5,197	5,150
12		5,945		6,345		5,732		5,896	
1	Not Heated	10,732		6,479		7,915		7,394	
2		8,367	9,937	7,880	7,789	7,814	8,318	7,742	7,624
3		10,712		9,008		9,225		7,736	
4	1500	5,482		5,379		4,513		4,689	
5		4,744	5,113	4,340	4,521	4,110	4,378	5,579	5,329
6		-		3,845		4,511		5,720	
7	1600	5,292		6,583		4,761		5,313	
8		4,849	5,071	5,568	5,495	4,663	4,687	5,594	5,394
9		-		4,334		4,637		5,274	
10	1800	4,708		3,573		4,361		5,675	
11		4,898	4,700	4,320	4,400	4,862	4,066	4,962	5,225
12		4,495		5,306		2,975		5,038	

1. Compressive strength (psi)
2. Average compressive strength (psi)

Table XI. Compressive Strength of Cement A Cubes Cured and Dried for 8 Days

Cube No.	Maximum Temperature (F)	Rate of Temperature Rise: 8 F/sec		10 F/sec		12 F/sec		14 F/sec	
		1	2	1	2	1	2	1	2
1	Not Heated	16,900		11,000		12,058		13,573	
2		13,157	15,167	11,301	10,507	10,986	12,043	10,429	11,035
3		15,443		9,219		13,084		9,104	
4	1000	6,990		5,441		5,495		5,290	
5		7,599	7,147	4,746	5,096	5,578	5,412	5,884	5,429
6		6,851		5,101		5,164		5,114	
7	1200	6,160		4,584		5,093		5,970	
8		5,892	5,945	3,985	3,888	4,783	4,887	5,063	5,399
9		5,783		3,096		4,786		5,164	
10	1400	6,058		5,368		3,930		5,355	
11		6,038	5,874	4,419	4,811	5,604	4,764	5,353	5,377
12		5,525		4,645		4,759		5,423	
1	Not Heated	13,392		13,081		13,790		12,594	
2		14,035	13,581	13,476	12,828	13,317	13,651	10,025	11,781
3		13,316		11,927		13,845		12,725	
4	1500	6,429		4,494		3,829		4,209	
5		-	6,531	6,076	5,761	4,353	4,194	4,698	4,311
6		6,632		6,713		4,401		4,025	
7	1600	6,118		3,448		5,766		4,912	
8		6,590	6,518	6,349	5,265	5,244	5,389	4,405	4,632
9		6,845		5,997		5,158		4,580	
10	1800	6,616		6,345		5,181		4,861	
11		6,335	6,632	5,241	6,076	5,611	5,233	3,890	4,427
12		6,944		6,641		4,908		4,530	

1. Compressive strength (psi)
2. Average compressive strength (psi)

Table XII. Compressive Strength of Cement A Cubes Cured and Dried for 29 Days

Cube No.	Maximum Temperature (F)	Rate of Temperature Rise							
		8 F/sec		10 F/sec		12 F/sec		14 F/sec	
		1	2	1	2	1	2	1	2
1		9,673		5,277		11,950		11,862	
2	Not Heated	10,327	10,080	5,896	5,893	11,807	11,372	10,789	10,649
3		10,240		6,506		10,359		9,296	
4		3,930		5,556		4,466		4,937	
5	1000	3,990	4,045	5,633	5,762	5,323	5,116	5,904	5,071
6		4,216		6,098		5,559		4,371	
7		3,216		5,100		4,291		5,552	
8	1200	3,000	3,387	4,798	5,313	3,746	4,037	5,717	5,347
9		3,945		6,040		4,075		4,773	
10		3,719		5,381		4,389		4,798	
11	1400	3,292	3,720	5,500	5,125	4,175	4,196	4,736	4,699
12		4,150		4,495		4,025		4,562	
1		11,219		4,686		12,218		11,558	
2	Not Heated	8,497	9,972	5,852	5,305	13,944	12,492	11,591	11,050
3		10,201		5,377		11,315		10,000	
4		3,556		5,917		4,070		4,861	
5	1500	3,481	3,657	3,766	4,120	4,458	4,391	5,452	5,029
6		3,933		2,678		4,645		4,774	
7		4,254		3,477		4,736		4,774	
8	1600	4,020	4,108	3,788	4,734	4,660	4,988	5,290	5,240
9		4,049		6,936		5,569		5,655	
10		3,975		7,602		7,582		5,177	
11	1800	3,778	4,272	4,848	6,218	4,924	6,253	5,417	5,232
12		5,062		6,203		-		5,101	

1. Compressive strength (psi)
2. Average compressive strength (psi)

Table XIII. Compressive Strength of Cement A Cubes Cured and Dried for 57 Days

Cube No.	Maximum Temperature (F)	Rate of Temperature Rise: 8 F/sec 1	8 F/sec 2	10 F/sec 1	10 F/sec 2	12 F/sec 1	12 F/sec 2	14 F/sec 1	14 F/sec 2
1	Not Heated	9,206		12,639		9,040		12,836	
2		7,550	8,637	11,935	11,851	7,085	9,003	9,295	11,311
3		9,154		10,980		10,885		11,803	
4	1000	4,506		4,367		4,636		5,333	
5		4,117	4,390	5,791	4,806	5,099	4,870	4,307	5,045
6		4,488		4,259		4,876		5,495	
7	1200	5,275		4,000		4,581		4,418	
8		4,633	4,830	4,585	4,272	5,283	4,840	5,419	4,718
9		4,583		4,230		4,655		4,316	
10	1400	4,031		4,684		5,125		4,912	
11		4,656	4,340	4,768	4,805	5,200	4,920	4,214	4,531
12		4,333		4,962		4,435		4,468	
1	Not Heated	6,826		11,824		7,606		9,499	
2		8,022	8,031	9,298	11,053	6,405	8,550	11,038	10,381
3		9,246		12,038		11,638		10,606	
4	1500	3,763		-		5,421		4,458	
5		3,928	3,732	4,987	4,987	6,305	5,723	4,825	4,719
6		3,505		-		5,444		4,874	
7	1600	3,838		4,000		5,985		4,458	
8		3,469	3,906	4,825	4,413	5,846	5,757	5,151	4,823
9		4,411		4,413		5,440		4,861	
10	1800	4,064		4,962		5,272		4,937	
11		3,807	3,906	4,637	4,800	5,322	5,226	4,812	4,741
12		3,848		-		5,074		4,474	

1. Compressive strength (psi)
2. Average compressive strength (psi)

Table XIV. Compressive Strength of Cement B Cubes Cured and Dried for 8 Days

Cube No.	Maximum Temperature (F)	Rate of Temperature Rise							
		8 F/sec		10 F/sec		12 F/sec		14 F/sec	
		1	2	1	2	1	2	1	2
1	Not Heated	9,106		10,541		13,086		8,250	
2		8,249	8,722	10,317	10,460	11,234	12,303	7,286	7,440
3		8,810		10,521		12,588		6,785	
4	1000	3,441		4,250		6,616		4,076	
5		4,547	4,034	3,837	4,217	6,429	6,289	4,535	4,227
6		4,114		4,565		5,821		4,070	
7	1200	3,977		4,255		5,167		3,354	
8		3,529	3,672	3,692	3,899	6,110	5,587	3,668	3,382
9		3,509		3,751		5,485		3,123	
10	1400	4,432		3,401		5,126		2,931	
11		3,728	4,012	4,188	4,005	4,910	4,995	3,109	2,861
12		3,875		4,427		4,949		2,544	
1	Not Heated	6,193		7,967		14,835		6,253	
2		7,570	6,837	9,287	8,350	15,200	15,062	6,338	6,798
3		6,747		7,797		15,150		7,802	
4	1500	4,125		3,973		5,687		4,459	
5		3,985	3,839	3,223	3,618	5,140	5,430	3,756	4,106
6		3,406		3,657		5,462		4,103	
7	1600	3,670		3,935		5,403		3,756	
8		3,645	4,011	3,486	3,452	4,974	5,079	3,551	3,627
9		4,719		2,934		4,861		3,573	
10	1800	3,258		3,890		6,256		4,115	
11		3,740	3,277	4,032	4,025	5,200	5,617	4,005	4,201
12		2,832		4,154		5,394		4,484	

1. Compressive strength (psi)
2. Average compressive strength (psi)

Table XV. Compressive Strength of Cement B Cubes Cured and Dried for 29 Days

Cube No.	Maximum Temperature (F)	Rate of Temperature Rise							
		8 F/sec		10 F/sec		12 F/sec		14 F/sec	
		1	2	1	2	1	2	1	2
1	Not Heated	6,583		4,055		9,225		6,477	
2		6,621	6,747	6,407	5,049	9,129	8,764	5,177	6,244
3		7,038		4,685		7,938		7,079	
4	1000	4,104		3,678		3,835		3,485	
5		4,563	3,958	4,158	3,676	4,963	4,247	3,826	3,666
6		3,207		3,191		3,943		3,687	
7	1200	4,211		3,191		3,643		3,501	
8		3,947	4,117	3,338	3,240	4,887	4,271	4,162	3,646
9		4,192		3,191		4,284		3,275	
10	1400	4,359		3,144		2,867		4,089	
11		5,241	4,783	2,746	3,017	3,920	3,543	4,284	4,301
12		4,749		3,160		3,843		4,530	
1	Not Heated	6,771		6,086		6,725		6,967	
2		7,513	6,975	6,184	5,857	5,114	6,453	10,101	8,408
3		6,641		5,302		7,519		8,157	
4	1500	4,158		3,207		3,108		3,980	
5		4,444	4,309	4,020	3,491	3,668	3,440	5,101	4,541
6		4,326		3,245		3,543		4,543	
7	1600	3,586		3,048		3,650		4,505	
8		3,892	3,776	3,288	3,039	3,618	4,022	4,419	4,435
9		3,851		2,781		4,799		4,381	
10	1800	3,633		3,359		4,127		5,114	
11		3,813	3,893	3,712	3,471	4,089	3,984	4,632	4,677
12		4,232		3,342		3,737		4,284	

1. Compressive strength (psi)
2. Average compressive strength (psi)

Table XVI. Compressive Strength of Cement B Cubes Cured and Dried for 57 Days

Cube No.	Maximum Temperature (F)	Rate of Temperature Rise							
		8 F/sec		10 F/sec		12 F/sec		14 F/sec	
		1	2	1	2	1	2	1	2
1	Not Heated	5,677		3,325		9,394		10,579	
2		6,520	5,783	5,251	4,731	6,784	8,296	8,535	9,053
3		5,152		5,616		8,709		8,046	
4	1000	3,079		3,668		4,472		4,177	
5		3,555	3,406	3,962	3,855	4,499	4,175	4,544	4,266
6		3,584		3,934		3,554		4,078	
7	1200	3,611		3,832		3,713		3,304	
8		3,038	3,215	4,822	4,522	3,854	4,005	3,829	3,650
9		2,997		4,911		4,449		3,816	
10	1400	3,702		3,671		4,015		3,530	
11		3,165	3,347	2,919	3,456	3,952	3,813	3,813	3,902
12		3,174		3,779		3,471		4,362	
1	Not Heated	6,721		4,316		5,606		8,207	
2		6,504	6,802	4,150	4,272	8,907	8,108	8,342	8,514
3		7,180		4,350		9,811		8,992	
4	1500	3,894		3,987		4,271		5,641	
5		3,359	3,682	4,273	4,471	4,318	4,316	5,539	5,603
6		3,794		5,152		4,358		5,628	
7	1600	3,672		5,050		4,442		4,453	
8		3,568	3,726	5,189	4,962	4,171	4,453	3,968	4,273
9		3,937		4,646		4,747		4,398	
10	1800	4,068		5,592		3,709		3,192	
11		4,013	3,744	4,239	4,759	3,965	3,705	3,267	3,557
12		3,152		4,442		3,442		4,213	

1. Compressive strength (psi)
2. Average compressive strength (psi)

Appendix C

DATA ANALYSIS FOR "THE RATE OF HEATING CEMENT PASTE"

Task Y-F015-15-107

by

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INTRODUCTION

"The objective is to determine if the rate of heating cement paste of a concrete mix is a contributing factor to the explosive spalling that takes place when concrete pavement surfaces are subjected to thermal shock."

In this investigation, five types of cement (Types I, II, III, A and B) were tested at the end of the 8-, 29- and 57-day curing cycle (these 15 combinations are designated as CT sets). Eight molds of cement were used for each CT set, and each pair was subjected to a temperature rate (R) of either 8, 10, 12 or 14 F per second. For the first mold, three control (unheated) compressive-strength determinations were made for each R value, and three such values were also taken at 1000, 1200 and 1400 F maximum temperatures. For the second mold, three control values and three readings each were taken at 1500, 1600 and 1800 F maximum temperatures.

The presence of two molds for each temperature rate, and the definite difference between molds that was found by a comparison of the control results, resulted in a model which would adjust for the differences and permit comparisons to be made between the factors of interest.

MODEL DESCRIPTION

The following model was fitted* to each CT set of data to reduce the data to a few characteristic parameters:

$$E\,X_{ijk} = \mu + \gamma_i + \beta_i M_j + \begin{cases} w\,Y_{2i-1} & \text{for } j = 1,2,3 \\ w\,Y_{2i} & \text{for } j = 4,5,6 \end{cases}$$

where: E signifies an expected value

X_{ijk} = average compressive strength of the treated values on the k^{th} mold ($k = 1, \ldots, 8$), for the i^{th} temperature rate ($i = 1, \ldots, 4$), and and the j^{th} maximum temperature ($j = 1, \ldots, 6$)

*See Appendix C-I for the details of the fitting procedure.

$$M_i = \left[6\left(\frac{L_i}{100} - 85\right) + 425\right],$$ a standardized maximum temperature:

i	1	2	3	4	5	6
L_i (°F)	1000	1200	1400	1500	1600	1800

C_k = average compressive strength in the control group of the k^{th} mold

$$Y_k = C_k - \frac{1}{8}\sum_{k=1}^{8} C_k$$

μ = average compressive strength for a particular CT set of data

γ_i = measure of the difference in average strength of cubes subjected to the i^{th} temperature rate from the average for the entire CT set of data (Note that $\gamma_1 + \gamma_2 + \gamma_3 + \gamma_4 = 0$ for each CT set)

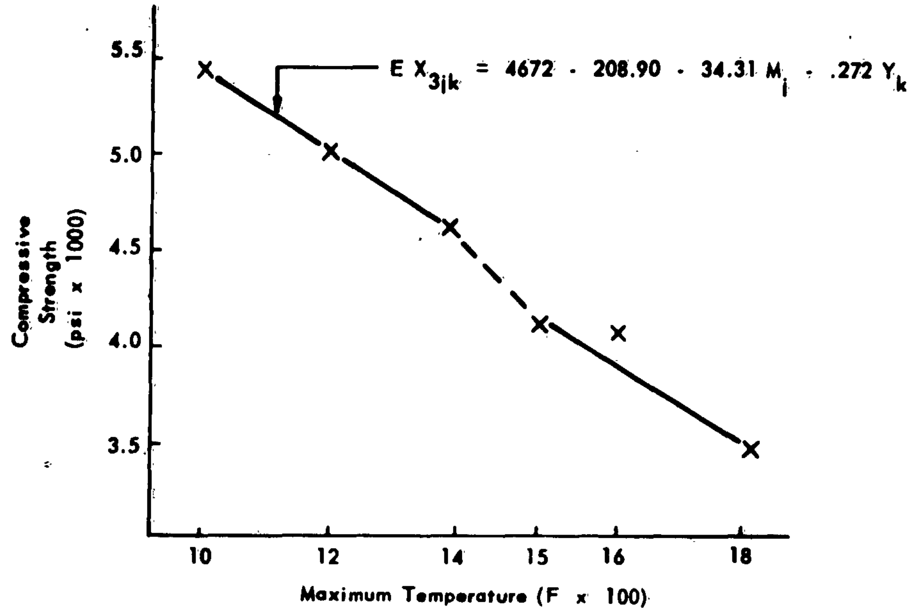
β_i = measure of the rate of decrease (if negative) of compressive strength for the cubes subjected to the i^{th} temperature rate

w = an adjustment for possible mold differences (covariable)

For each temperature rate, within a CT set of data, it is assumed that a straight line adequately represents the relationship of compressive strength to maximum temperature, with perhaps a displacement due to mold differences. A satisfactory fit (see below) would mean that the μ, γ and β values could be conveniently analyzed for the effect of Temperature Rate (R), Curing Condition (C), and Cement Type (T).

GOODNESS OF FIT

For each CT set of data, μ, γ_i, β_i and w were estimated from the data averages by the method of least squares. These values may be found in Appendix C-II. For example, for the Type I cement, the 8-day curing condition and temperature rate of 12 F per second, the following graph shows the observed averages as well as the fitted line.



The good agreement between the observed and computed values found above is confirmed by the quantitative analysis found in Appendix C-III.

There were no unaccounted trends in the deviations of the averages from their computed values within a given CT set; also, the deviations of the individual values from their expected values are shown to be consistent for the different CT sets. Therefore, since the proposed model is found to fit the observed data, the calculated parameters may be considered to be meaningful summary measures of this experiment.

ANALYSIS*

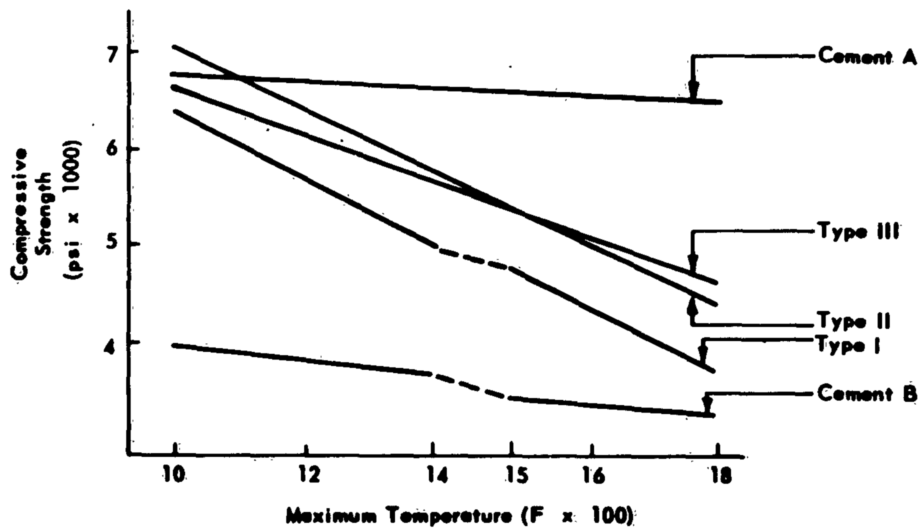
Heating Rate (R). Although the average β value was -20.8 for the low rates (8 and 10 F per second), while it was -25.9 for the high rates (12 and 14 F per second), this difference may well be due to chance. This is true even though the differences between the two low-rate average β's and between the two high-rate average β's are considerably smaller.

*See Appendix C-IV for the Analyses of Variances which justify the statements in this section.

Curing Condition (C). The average β under the 8-day and 29-day curing conditions was -27.7, while it was only -14.6 for the 57-day condition. This difference is found to be larger than attributable to chance. There is essentially no difference in the average of the increase from 8 to 29 days.

Cement Type (T). This factor produced the largest effect. The average β was -39.0 for Types I, II and III cement, while it was zero for the Cement A and Cement B group. Also, this same grouping resulted in an average μ of 1485 for the first group and 1125 for the second.

For example, for the 8-day curing cycle at a temperature rate of 8 F per second, the following is illustrative of the difference in β values:



Interactions. In no case was there a significant interaction between any of the factors considered. This implies that the (main) effects presented above do not have to be considered as dependent on the values of one of the other factors but may be given individual consideration.

CONCLUSIONS

1. Of the factors considered in this report, the difference between the calcium aluminate cements and portland cements proved to be the most prominent. In general, the calcium aluminate cements yielded a lower average compressive strength but were less affected by differences in maximum temperature.

2. On the average, higher heating rates produced no appreciable effect on the level of compressive strength or in the rate of decrease of strength with increased maximum temperature.

3. Although the increase of curing time from 8 days to 29 days produced no significant effect, the 57-day condition did result in a more stable compressive strength.

4. A model is found to fit the data quite satisfactorily which permits an analysis of the original data in terms of meaningful parameters, and at the same time adjusts for the confounding influence of mold effects.

Appendix C-I

FITTING MODEL TO DATA

1. Original Data:

The averages of identically treated samples (usually 3) are arranged in the following format.

i	Coded Temp. (M_i)	Rates (R_j)			
		R_1	R_2	R_3	R_4
	Control	C_1	C_3	C_5	C_7
1	-25	X_{111}	X_{213}	X_{315}	X_{417}
2	-13	X_{121}	X_{223}	X_{325}	X_{427}
3	-1	X_{131}	X_{233}	X_{335}	X_{437}
	Control	C_2	C_4	C_6	C_8
4	5	X_{142}	X_{244}	X_{346}	X_{448}
5	11	X_{152}	X_{254}	X_{356}	X_{458}
6	23	X_{162}	X_{264}	X_{366}	X_{468}

2. Model:

$$i = 1,2,3 \qquad\qquad i = 4,5,6$$

$$E\,X_{1i1} = \mu + \gamma_1 + \beta_1 M_i + w\,y_1 \qquad E\,X_{1i2} = \mu + \gamma_1 + \beta_1 M_i + w\,y_2$$

$$E\,X_{2i3} = \mu + \gamma_2 + \beta_2 M_i + w\,y_3 \qquad E\,X_{2i4} = \mu + \gamma_2 + \beta_2 M_i + w\,y_4$$

$$E\,X_{3i5} = \mu + \gamma_3 + \beta_3 M_i + w\,y_5 \qquad E\,X_{3i6} = \mu + \gamma_3 + \beta_3 M_i + w\,y_6$$

$$E\,X_{4i7} = \mu + \gamma_4 + \beta_4 M_i + w\,y_7 \qquad E\,X_{4i8} = \mu + \gamma_4 + \beta_4 M_i + w\,y_8$$

3. Estimates of μ, γ_i, β_i, w:

$$\hat{\mu} = \bar{x}$$

$$\hat{w} = \left\{F - \sum_{i=1}^{4} S_i \bar{x}_i - \frac{1}{1,470} \sum_{i=1}^{4} v_i z_i\right\} \div \left\{T - \frac{1}{6} \sum_{i=1}^{4} S_i^2 - \frac{1}{1,470} \sum_{i=1}^{4} v_i^2\right\}$$

$$\hat{\gamma}_i = (\bar{x}_i - \bar{x}) - \frac{1}{6} \hat{w} S_i$$

$$\hat{\beta}_i = \frac{1}{1,470} (z_i - \hat{w} v_i)$$

4. Computations:

$$4.1\ \bar{C} = \frac{1}{8} \sum_{k=1}^{8} C_k$$

$$Y_k = C_k - \bar{C}$$

$$4.2\ v_i = 39 (Y_{2i} + Y_{2i-1})$$

$$4.3\ S_i = 3 (Y_{2i} + Y_{2i-1})$$

$$4.4\ T = 3 \sum_{k=1}^{8} Y_k^2$$

$$4.5\ z_i = \sum_{j=1}^{6} M_j X_{ijk}$$

$$\begin{aligned} 4.6\ F = {} & Y_1 (X_{111} + X_{121} + X_{131}) \\ & + Y_2 (X_{142} + X_{152} + X_{162}) \\ & + \qquad \cdot \\ & + \qquad \cdot \\ & + \qquad \cdot \\ & + \qquad \cdot \\ & + \qquad \cdot \\ & + Y_8 (X_{448} + X_{458} + X_{468}) \end{aligned}$$

$$4.7\ \bar{x}_i = \frac{1}{6} \sum_{j=1}^{6} X_{ijk}$$

$$4.8\ \bar{x} = \frac{1}{4} \sum_{i=1}^{4} \bar{x}_i$$

5. Example:

Type I cement cured 57 days

i	Max Temp (F)	R_1	R_2	R_3	R_4
	Control	5,706	7,625	8,299	8,103
1	1000	4,552	5,736	5,831	6,932
2	1200	4,390	5,670	5,546	6,422
3	1400	4,882	4,781	4,653	5,820
	Control	6,636	6,670	7,638	8,395
4	1500	4,784	4,984	4,953	5,602
5	1600	5,166	4,376	5,084	5,319
6	1800	4,092	4,743	4,790	5,334

$\bar{C} = 7,384$

k	1	2	3	4	5	6	7	8
Y_k	-1,678	-748	241	-714	915	254	719	1,011

e.g., $Y_5 = 8,299 - 7,384 = 915$

i	v_i	S_i	z_i	$\bar{x}_i$
1	36,270	-7,278	-890	4,644.333
2	-37,245	-1,419	-39,746	5,048.333
3	-25,779	3,507	-31,667	5,142.833
4	11,388	5,190	-53,405	5,904.833

e.g., $v_2 = 39(Y_4 - Y_3) = 39(-714 - 241) = -37,245$

$S_3 = 3(Y_6 + Y_5) = 3(254 + 915) = 3,507$

$z_2 = (-25)(5,736) + \ldots + (23)(4,743) = -39,746$

$\bar{x}_1 = \frac{1}{6}(4,552 + \ldots + 4,092) = 4,644.333$

$$T = \left[(-1,678)^2 + \ldots + (1,011)^2\right] = 19,151,666$$

$$F = (-1,678)(4,552 + 4,390 + 4,882) + \ldots + (8,395)(5,602 + 5,319 + 5,334) = 8,784,851$$

$$\bar{x} = \frac{1}{4}(4,644.843 + 5,048.343 + 5,142.844 + 5,904.845) = 5,185.083$$

$$\hat{w} = \frac{8,784,851 - 7,713,333.387 - (\frac{39}{1,470})(42,467,357)}{19,151,666 - (\frac{1}{6})(94,217,994) - (\frac{1,521}{1,470})(2,299,110)}$$

$$= \frac{-55,162.368}{1,069,789.954} = -.0549$$

i	$\hat{\gamma}_i$	$\hat{\beta}_i$
1	-607.407	.750
2	-149.746	-28.430
3	-10.130	-22.506
4	767.284	-35.905

$\hat{\mu} = 5,185.083$

Appendix C-II

PARAMETER ESTIMATES

Cement Type	Curing Conditions (Days)	μ	Temperature Rate (F/sec) 8		10		12		14		w
			γ_1	β_1	γ_2	β_2	γ_3	β_3	γ_4	β_4	
I	8	4,672	515.58	-54.37	38.48	-32.93	-208.90	-34.31	-345.16	-9.37	-.272
	29	6,258	-36.97	-37.56	275.25	-60.17	101.69	-58.01	-339.97	-14.13	-.226
	57	5,185	-607.41	.75	-149.75	-28.43	-10.13	-22.51	767.28	-35.90	-.055
II	8	6,143	-338.95	-53.01	-515.88	-33.50	-519.14	-44.51	1,373.96	-35.68	.050
	29	7,735	-927.58	-46.41	-188.76	-73.96	1,449.48	-66.92	-333.14	-56.03	.087
	57	6,055	583.26	-29.44	-363.09	5.48	-775.39	-42.95	555.22	-37.65	1.053
III	8	6,237	41.41	-34.87	93.22	-49.99	305.99	-58.43	-440.62	-74.93	.809
	29	5,965	-109.60	-48.34	-204.24	-46.36	-30.29	-35.40	344.14	-49.46	.286
	57	5,211	85.06	-17.41	-27.22	-27.37	-312.51	-33.73	254.68	-24.95	-.126
Cement A	8	5,375	1,075.40	-3.58	-230.03	30.05	-393.70	-1.82	-451.68	-25.04	-.005
	29	4,753	-1,166.48	10.63	3,089.23	8.51	-1,453.39	5.01	-469.35	-5.54	.657
	57	4,713	-846.34	-20.66	302.95	-2.13	284.97	12.82	258.41	-9.45	-.209
Cement B	8	4,228	-296.19	-5.85	-351.65	-3.77	969.88	-20.68	-322.04	4.32	.072
	29	3,898	239.63	-3.41	-517.50	-5.21	-13.66	-5.67	291.52	21.85	.043
	57	4,036	-988.49	29.93	-1,468.26	10.08	952.44	-6.66	1,504.31	-11.16	-.724

Appendix C-III

QUANTITATIVE ANALYSIS FOR MS AND F VALUES

The following table of mean-square* (MS) and F values shows how well the average and individual compressive-strength values conform to the model. (The 5-percent significance value is 2.6.)

Source	Degree of Freedom	Cement Type														
		I			II			III			Cement A			Cement B		
		Curing Condition (days)														
		8	29	57	8	29	57	8	29	57	8	29	57	8	29	57
Regression	8	117	164	109	340	552	71	313	136	65	144	102	51	170	49	43
Deviations	15	14	20	11	37	32	25	26	7	14	29	37	9	19	11	27
Residual	48	7.4	9.5	6.4	18.2	38.2	7.0	16.6	8.2	7.8	9.7	11.2	3.9	8.3	4.0	4.6
F Values with 8, 15 df		8	8	10	9	17	3	12	20	5	5	3	6	9	5	2

Since the ratios of the Regression MS to the corresponding Deviations MS values are high (14 out of the 15 F values are significant), a great deal of the variation in the averages is accounted for by the fitted model. The homogeneity of the Deviations MS values** shows the consistency of the deviations from their predicted values. The Deviations MS values were checked by computing the sums of squares of deviations from the predicted values. Unaccounted trends in the deviations were missing. The homogeneity of the Residual MS values, with the exception of the 38.2, gives evidence of the consistency of the individual values with the model.

* Original values multiplied by 10^{-2}.

** An observed value of 5.36 for Hartley's test being nonsignificant (see Biometrika, December 1950, "Maximum F-Ratio as a Short Cut Test for Heterogeneity of Variance," by H. O. Hartley).

Appendix C-IV

ANALYSES OF VARIANCE OF PARAMETER ESTIMATES

Notation:

a - The 8, 10, 12 and 14 numbers under Temperature Rate are in °F/sec.

b - "A" is Cement A, and "B" is Cement B.

c - The 8, 29 and 57 numbers under Curing Condition are in days.

d - The notation (8, 10) vs (12, 14) refers to the single degree of freedom (df) effect of the high rates versus the low rates.

e - The notation T x [(8, 10) vs (12, 14)] refers to the four degrees of freedom corresponding to the interaction of Cement Type with the high and low rates.

f - The ( ) under df indicates that this effect is subdivided into the following comparisons.

g - All original values multiplied by 10^{-2} for the purpose of these tables.

Analysis of Variance of μ Values

Source of Variation	df	SS	MS
Cement Type (T)	(4)	1,117.465	279.37
(I, II, III) vs (A, B)	1		746.49
(I) vs (II)	1		243.04
(A) vs (B)	1		119.60
(I, II) vs (III)	1		8.34
Curing Condition (C)	(2)	117.033	58.52
(8, 29) vs (57)	1		25.22
(8) vs (29)	1		91.81
C x T	(8)	282.352	35.29
Total	14	1,516.850	

Analysis of Variance of β_i Values

Source of Variation	df	SS	MS
Temperature Rate (R)	(3)	4.790	1.60
(8, 10) vs (12, 14)	1		3.93
(12) vs (14)	1		.85
(8) vs (10)	1		.01
Cement Type (T)	(4)	228.060	57.01
(I, II, III) vs (A, B)	1		219.93
(I) vs (II)	1		6.78
(A) vs (B)	1		.01
(I, II) vs (III)	1		1.34
Curing Condition (C)	(2)	23.224	11.61
(8, 29) vs (57)	1		23.07
(8) vs (29)	1		.15
T x R	(12)	28.698	2.39
T x [(8, 10) vs (12, 14)]	4		1.27
Remainder (R x T)	8		2.95
C x R	(6)	17.390	2.90
C x [(8, 10) vs (12, 14)]	2		3.67
Remainder (C x R)	4		2.51
C x T	(8)	31.629	3.95
Residual (E)	24	54.628	2.28
Total	59	388.420	

Analysis of Variance of γ_i Values*

Source of Variation	df	SS	MS
Temperature Rate (R)	(3)	99.286	33.09
(8, 10) vs (12, 14)	1		59.80
(12) vs (14)	1		17.64
(8) vs (10)	1		21.85
T x R	(12)	914.578	76.21
T x [(8, 10) vs (12, 14)]	4		147.32
Remainder (T x R)	8		40.66
C x R	(6)	490.729	81.79
C x [(8, 10) vs (12, 14)]	2		123.12
Remainder (H x T)	4		61.12
Residual (E)	24	1,796.719	74.86
Total	45	3,301.312	

* Since $\sum_{i=1}^{4} \gamma_i$ was forced to equal zero, the C, H and C x H effects are identically zero.

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